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PLASMA WAVE EXPERIMENT

(A presentation of the device and
first experimental results)

M. Bitter, P.J. Paris

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Ecole Polytechnique Fédérale de Lausanne

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Introduction

The experimental device was originally designed by G. Landauer as a part of the ESRO space research program carried out in Frascati. It allows to produce stationary or pulsed collisionless low- β -plasmas, which are appropriate for the investigation of plasma phenomena resulting from the collective motions of free streaming particles.

The machine has been transferred to this laboratory in 1973 and is again in operation since last December. The experimental work, which is to be carried out on the machine, is concerned with plasma instabilities.

Here we give a description of the device (section I) and a report on our first experimental results concerning the plasma diagnostics with Bernstein waves (section II) and the observation of instabilities produced by a double humped electron velocity distribution (section III). These results have also been presented at the Réunion de la Société Suisse de Physique, Berne, 26-27 April 1974.

Lausanne

I. THE DEVICE

1. General description

The experimental device is a glow discharge, which is shown in fig. 1. A hot cathode of 5 cm diameter emits electrons, which are accelerated by a positive potential applied to a grid anode about 5 cm in front of the cathode. Collisions between these primary electrons and the neutral gas produce a plasma of moderate electron density and temperature, which is radially confined by a homogeneous magnetic field. The dimensions of the plasma column are given by the diameter of the cathode and the anode-cathode distance, which is about 75 cm.

The plasma diagnostics are performed by means of electrical probes, which are used as Langmuir probes and antennas to measure the propagation properties of Bernstein waves.

2. Cathode

The sintered Ni - Ba Sr CO₃ cathode used for the experiment yields a maximum electron flux of about 40 [A/cm²]. The cathode is kept at a constant temperature of about 800 °C by heat radiation from a tungsten filament (10 V, 80 A).

3. Magnetic field

The magnetic field is produced by 14 water cooled coils of 27 cm diameter, which can maintain magnetic fields up to 3 [kgauss] uniform to better than 3 % over the working volume. The cooling system for the magnet, which is layed out for a maximum cooling power of 150 [KW], yields a water flux of 40 [l/min] at a pressure of 8 [atm].

4. Electrical probes

The electrical probes consist of a INOX wire of .3 mm diameter, which (apart from the short piece of a few millimeter length forming the probe tip) is surrounded by a thin isolating tube of ceramics and an outer shielding INOX tube. The r.f. impedance of the probe is adjusted to a value close to 50Ω by an appropriate choice of the ceramic material and the probe dimensions . The probes are motorised for longitudinal and rotational motion.

5. Plasma parameters

The discharge characteristics, i.e. the voltage between cathode and grid as a function of the current drawn by the grid, are shown in fig. 2 for typical values of the neutral gas pressure (5×10^{-4} Torr) and the magnetic field (a few hundred gauss).

The data of the plasmas produced for these discharge conditions are given below:

plasma density:	$10^7 - 10^{10}$	[p/cm ³]
electron temperature:	1 - 5	[e V]
ion temperature:	.1 - .5	[e V]
electron gyroradius:	$\approx .5$	[mm]
mean free path (electron neutral collisions)for Argon at a gas pressure of 5×10^{-4} [mm Hg] * :		
Electron energy [eV]	1	12 25
Mean free path [cm]	650	23(min.) 39

* Brown S.C., Basic Data of Plasma Physics, M.I.T. Press Cambridge, Massachusetts 1959.

II. PLASMA DIAGNOSTICS WITH BERNSTEIN WAVES

Introduction

Bernstein waves [1] have been investigated by a number of authors [2] - [8]. As the dispersion depends on the electron plasma frequency ω_p and the electron gyroradius R , it is possible to determine these parameters from the characteristics of wave propagation. This requires, however, knowledge of the dispersion relations, which are functions of the electron velocity distribution. Calculations for different distributions are given in the literature [7] - [8].

Thus, the electron velocity distribution must be known, in order to decide which dispersion relations are the adequate ones for a certain experiment. This is a report on plasma diagnostics with Bernstein waves, where Langmuir probes have been used as a supplementary tool.

Theory

The electrostatic approximation [9], which is valid for Bernstein waves, yields

$$\vec{k} \parallel \vec{E} \quad (1)$$

and

$$\epsilon_{xx} k_x^2 + 2 \epsilon_{xz} k_x k_z + \epsilon_{zz} k_z^2 = 0 \quad (2)$$

where \vec{k} , \vec{E} and ϵ_{ij} are the wave vector, the electric field of the wave and the components of the permittivity tensor, respectively. The dispersion relation (2) reduces to

$$\epsilon_{xx} = 0 \quad (3)$$

for a propagation perpendicular to the magnetic field ($\vec{B} = B \hat{z}$). Eq. (3) has solutions with real values of ω and k , yielding a series of propagation passbands (fig. 3), for the expression derived by Bernstein [1] for the case of a Maxwellian velocity distribution

$$\epsilon_{xx} = \epsilon_0 \left\{ 1 - \left(\frac{\omega_p}{\omega_c} \right)^2 \sum_{n=1}^{\infty} \frac{\exp[-\lambda] I_n(\lambda)}{\left(\frac{\lambda}{2} \right) \left[\left(\frac{\omega}{n\omega_c} \right)^2 - 1 \right]} \right\} \quad (4)$$

with $\omega_c = \frac{eB}{m}$ and $\lambda = (kR)^2$.

These waves can be excited applying a r.f. voltage to an antenna immersed in the plasma, provided that the antenna orientation allows for a propagation perpendicular to the magnetic field. This condition is easily matched as a result of condition (1) and the fact that the electric field is perpendicular to the antenna surface. The electric field is then related to the external charge, ρ_{ext} , on the antenna by the equation [3]

$$\epsilon_{\perp}(k, \omega) \vec{E}(k, \omega) = \frac{i \vec{k} \rho_{\text{ext}}}{k^2} \quad (5)$$

The inverse Fourier transform

$$E(x, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{i g_{\text{ext}} e^{-ikx}}{k \epsilon_{\perp}(k, \omega)} dk$$

is determined by the zeros of $\epsilon(k, \omega)$. It can be expressed as a sum of two components

$$E(x, \omega) = \underbrace{\frac{1}{2\pi} p \int_{-\infty}^{\infty} \frac{i g_{\text{ext}} e^{-ikx}}{k \epsilon_{\perp}(k, \omega)} dk}_{\text{(capacitive signal)}} + \underbrace{\sum \text{Residues (for } \epsilon_{\perp}^{(6)} = 0)}_{\text{(wave signal)}}$$

where the first term, the principal value of the integral, is independent of k and the second term, the contribution from the poles of the integrand, gives the electric field of the excited waves.

Experiment

The measurements have been performed in the positive column of an argon gas discharge of 75 cm length and 5 cm \emptyset with plasma densities ranging from $10^7 - 10^9 \text{ cm}^{-3}$ and homogeneous magnetic fields of a few hundred gauss.

The Langmuir probes consist of a small cylindrical (.3 mm \emptyset , 5 mm length) probe and a flat probe of 2.5 cm \emptyset (central part of the ring anode, fig.1).

The measurements with the cylindrical probe give only an indication of the magnitude of the plasma parameters, since the probe dimensions are

comparable with the Debye length and the electron gyroradius [10] - [12].

The flat probe, which has been shielded by a fine meshed grid, to keep the influence of the probe current on the discharge parameters negligible, was used to measure the electron velocity distribution parallel to the magnetic field. This distribution was found to be double humped with a major Maxwellian like peak at the plasma potential of about 3 volt and another peak at about 30 eV.

Bernstein wave dispersion relations for this type of electron velocity distribution (beam - plasma system) have been calculated [8]. Significant deviations from the dispersion behaviour shown in fig. 3 may occur for values of $\left(\frac{\omega_{pb}}{\omega_c}\right)^2 \approx 20$ (where ω_{pb} is the plasma frequency of the beam) due to a coupling of the dispersion branches of successive passbands. However, since for our experiment $\left(\frac{\omega_{pb}}{\omega_c}\right)^2 < 1$ and $\left(\frac{\omega_{pb}}{\omega_p}\right)^2 \approx 1$, the dispersion curves in fig. 3 are applicable to a good approximation.

The pair of parallel thin wire (.3 mm ϕ , 15 mm length) antennas shown in fig. 1 has been used to excite and detect the Bernstein waves. Two techniques have been applied:

- A. 1. The transmitted signal was measured as a function of the magnetic field for a fixed frequency ω_1 , which was expected to be higher than ω_p . The transmitted signal (fig. 4) shows a series of maxima at $\omega_1 = n \omega_c$ and minima within the passbands, when ω_1 corresponds to a maximum $\left(\frac{d\omega}{dk} = 0\right)$ of the dispersion curve. A very pronounced minimum (cut off) appears for $\omega_1 = (\omega_p^2 + \omega_c^2)^{\frac{1}{2}}$, which allows the determination of ω_p .
2. A second measurement of the transmitted signal as a function of the antenna separation for a frequency $\omega_2 < \omega_1$ with the magnetic field kept at the value for which $\omega_1 = (\omega_p^2 + \omega_c^2)^{\frac{1}{2}}$, yields an interference pattern (fig. 5) between the direct capacitively

coupled signal and the wave signal (equ.(6)). With the wavelength obtained from this measurement and the dispersion relation determined by the first measurement, one gets the electron gyroradius.

- B. The wavelengths are measured for two frequencies $\omega_1 = 1.5$ and $\omega_2 = 2.5 \omega_c$ with the method of interference described above. The advantages of this technique are that the discharge parameters remain constant with the constant magnetic field and that for the special choice of the frequencies ω_1 , ω_2 expression (4) can be represented by a simple integral [4].

When measuring the wavelength care was taken that the applied signal frequency was smaller than the upper hybrid frequency ω_T in order to avoid errors due to the excitation of more than one Bernstein mode, which is possible for $\omega > \omega_T$ (see fig. 1).

Results

The plasma parameters have been determined for a series of discharge currents by the methods described above. The results are given in the table. The density values measured with Langmuir probes are smaller than those obtained with the Bernstein waves by a factor 2-3. A larger discrepancy exists with respect to the measured values of the electron temperature. The value of about 5 eV for the parallel electron temperature measured with the flat probe has also been confirmed by measurements of the ion acoustic wave velocity. Therefore we must conclude that the electron velocity distribution in our plasma shows considerable anisotropy.

	BERNSTEIN WAVES				LANGMUIR PROBES			
I_D [mA]	v_{ce} $\times 10^8$ [c/s]	R [mm]	n $\times 10^8$ [cm ⁻³]	T_e [eV]	CYLINDRICAL		FLAT	
					n $\times 10^8$ [cm ⁻³]	T_e [eV]	n $\times 10^8$ [cm ⁻³]	T_e [eV]
200	2	.43	23.5	.81	8.7	3.2	16	5.0
180	2	.44	20.2	.86	7.5	3.1	12.8	5.4
150	2.1	.43	19.7	.91	6.0	3.1	9.2	5.2
130	2.3	.30	13.3	.55	5.2	2.8	5.6	6.0
105	2.2	.34	10.7	.62	4.1	3.0	5.3	5.2
75	1.1	.70	6.2	.63	2.6	3.5	3	5.8
60	1.3	.34	2.9	.22	1.4	5.9	2	7.7

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III. PRODUCTION OF A DOUBLE HUMPED ELECTRON VELOCITY DISTRIBUTION FOR OBSERVATION OF PLASMA INSTABILITIES

I n t r o d u c t i o n

Double humped electron velocity distributions are of great interest in plasma physics as they lead to spontaneous excitation and growth of waves. The basic theory of electron beam-plasma systems has been given by Briggs [1] - [2]. However, the agreement between theory and experiment is often unsatisfactory, as the beam-plasma interactions are strongly affected by the finite boundaries of the experimental systems [3] - [7]. In particular, the finite length of a plasma column, which is usually not taken into account in most theoretical work, may have an important effect on the frequency spectrum of the excited waves.

Here we report on first observations with a double humped electron velocity distribution, whose shape can be modified by simple experimental means.

E x p e r i m e n t

1. Measurement of the electron velocity distribution

The experimental apparatus used and the typical parameters of our plasma have been presented in the previous paper on plasma diagnostics . Here we give a more detailed description of our measurements of the electron velocity distribution.

The central part (2.5 cm \emptyset) of the ring anode, which has been used to measure the electron velocity distribution parallel to the magnetic field, has been shielded against the cathode part of the discharge by means of a (movable) fine meshed (325 lines/inch) grid, in order to keep the influence of the probe current on the discharge parameters negligible. Evidence of the shielding effect is given by the fact that the discharge current/voltage, the floating potential of the grid and the ion saturation current drawn by the cylindrical probe in front of the anode, which is a measure of the plasma density, remained constant with the anode bias.

A typical example of a Langmuir characteristic taken with the anode is shown in fig. 6 . The first derivative of the characteristic with respect to the anode potential, which is also shown in fig. 6 , is directly proportional to the electron velocity distribution.^{*)} This is because the number of particles collected by the probe is neither sheath nor orbit limited, as the dimensions of the probe are large compared to the Debye length and the electron gyroradius (~ 0.5 mm) [9].

The distribution in fig. 1 shows a Maxwellian like peak at the plasma potential of 3 volts and another peak at about 30 eV.

^{*)} The differentiation technique used is described in the Appendix.

2. Nature of the double humped electron velocity distribution

At first view, one may try to ascribe the fast electron peak of the distribution to the primary electrons, which are emitted from the cathode and then accelerated by the voltage difference between the cathode and the first grid. However, this is not in agreement with the potential along the plasma column (fig. 6).

As the mesh width of the shielding grid was smaller than the Debye length, it is impossible that the primary electrons, which have only a velocity spread of the order of the cathode temperature (1000 °C), could overcome the potential barrier of four volts existing between the grid and the cathode (fig. 6). Therefore one must conclude that the electrons are produced by secondary emission at the grid itself.

The electrons are then accelerated by the potential drop towards the grid and gain sufficient kinetic energy to ionize the neutral gas.

The most relevant processes of secondary emission of electrons are the direct and the two stage Auger process, i.e. secondary emission of electrons from a metal surface by a bombardment with positive ions and metastable atoms, respectively [10]. The essential of these processes is that the energy distribution of the secondary electrons as well as the γ -coefficient (number of secondaries/particle impinging on the surface) are independent of the kinetic energy of the impinging particles, since the energy needed to eject an electron out of the metal is derived from the internal energy of the projectile (potential ejection). Measurements of the γ -coefficient for H_e^+ and A^+ on atomically

clean tungsten^{*)}, yield values of .24 and .12, respectively [11], which demonstrate the importance of the direct Auger process.

In order to prove experimentally the assumption of secondary emission of electrons from the shielding grid, we have measured the electron velocity distribution as a function of the grid potential. Since according to these measurements (fig.7-9) the fast electron peak appears exactly at the value of the grid potential, the above assumption can be accepted as valid.

An additional peak appears in the velocity distributions of fig. 2, if the grid is more positive than the cathode. This peak, which is fixed at the value of cathode potential, represents the primary electrons.

In order to decide, which of the two Auger processes is the dominant one, we have repeated the measurements with nitrogen, which unlike to the noble gas has no metastable state. As these measurements showed the same behaviour, we conclude that the direct Auger process is dominant.

3. Some observations of instabilities

The frequency spectrum of the noise present in our plasma shows a series of peaks at discrete frequencies and is a function of the discharge parameters, the grid potential and the length of the plasma column (anode-grid distance). Fig.10 shows the frequency spectra obtained for two different lengths of the plasma column.

^{*)} The γ -coefficient is reduced by about a factor 2 and almost independent of the nature of the metal, if the metal surface is covered by a monolayer of gas atoms [12].

We have also measured the noise intensity as a function of position along the plasma column for the frequency, where the main peak in the spectrum occurred. Fig.10 shows that the intensity varies almost periodically with position. This indicates the formation of a large amplitude standing wave.

C o n c l u s i o n

We have presented a double humped electron velocity distribution, which is produced by secondary emission of electrons from a fine meshed grid. The distribution can be easily modified by varying the grid potential. Preliminary investigation of the noise spectrum shows that plasma modes of well defined frequencies and wavelengths are driven unstable.

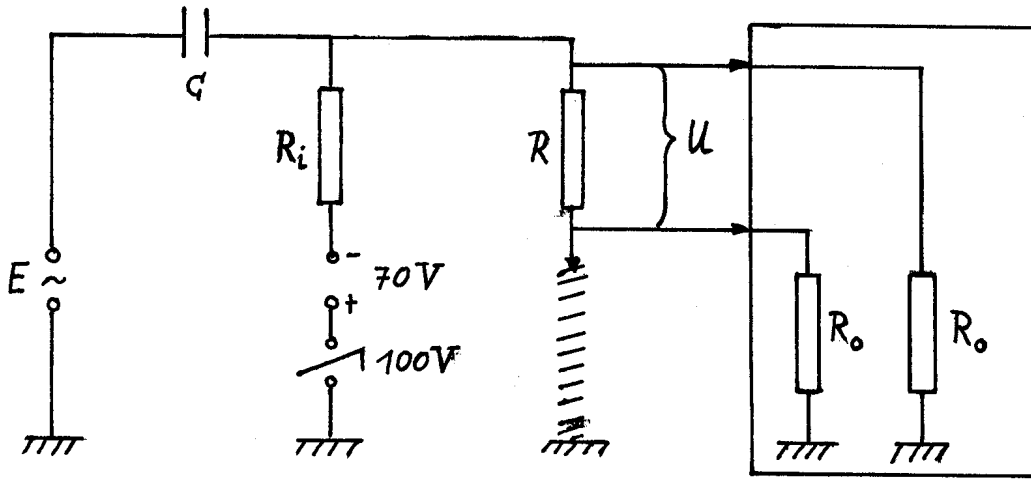
R e f e r e n c e s

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Appendix

The first derivative of the Langmuir characteristic was obtained measuring the a.c. component of the probe current by means of a phase sensitive detector tuned to the frequency of an a.c. voltage signal applied to the probe. The circuit is shown below.



The a.c. signal E is added via a coupling capacitance C to a slow (100 volt/5 sec) voltage sweep applied to the probe, and the voltage U developed across R by the probe current is fed into the differential input of the p.s.d. with input impedance R_o .

Using

$$(1) \quad E - \tilde{V}_c = R_g \tilde{I}_c$$

with

$$\frac{1}{R_g} = \frac{1}{R_i} + \frac{1}{R_o} + \frac{1}{R + (R_o \parallel r_p)}$$

where $r_p(V) = \frac{dV}{dI_p}(V)$ is the differential resistance of the Langmuir characteristic.

and

$$(2) \quad \tilde{I}_c = i \omega C \tilde{V}_c$$

one gets

$$(3) \quad \tilde{U} = R \frac{E - \tilde{V}_c}{R + (R_o \parallel r_p)} = \frac{R}{R + (R_o \parallel r_p)} \frac{i \omega R_g C}{1 + i \omega R_g C} E$$

The circuit differentiates, if $\tilde{U} \sim 1/r_p$. This condition is satisfied, if $R_o \gg r_p$ and $R \ll r_p$ and $\omega R_g C \gg 1$.

Since the differential resistance r_p of the Langmuir characteristic (fig. 1) is in the range $1k\Omega < r_p < 1M\Omega$, we have chosen $R_i = 1k\Omega$, $R = 10 \Omega$, $R_o = 100 M\Omega$, $C = 6.7 \mu F$, $\nu = 1 kHz$. This yields $20 < \omega R_g C < 40$, as R_g varies with r_p .

Acknowledgements

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PLASMA WAVE EXPERIMENT

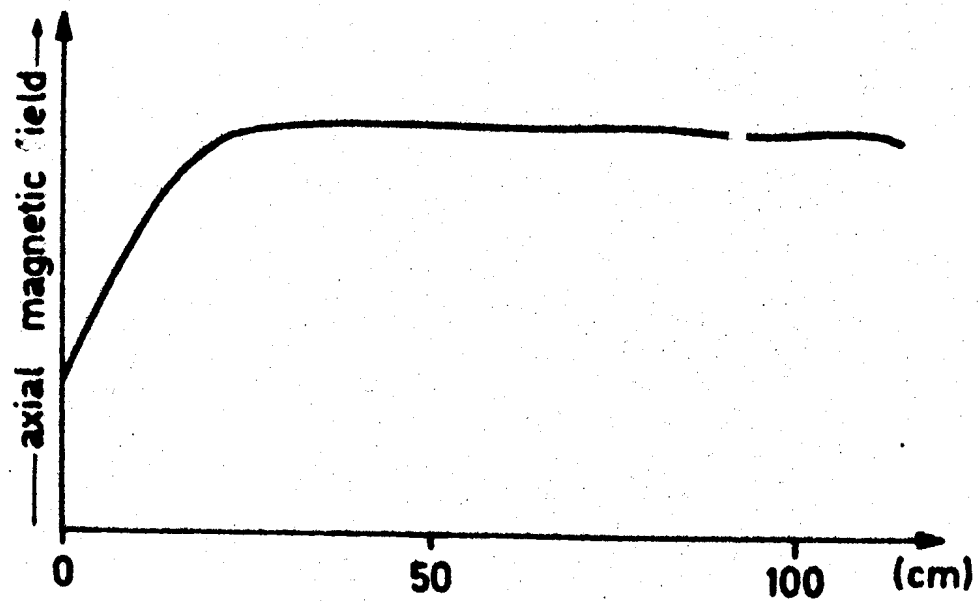
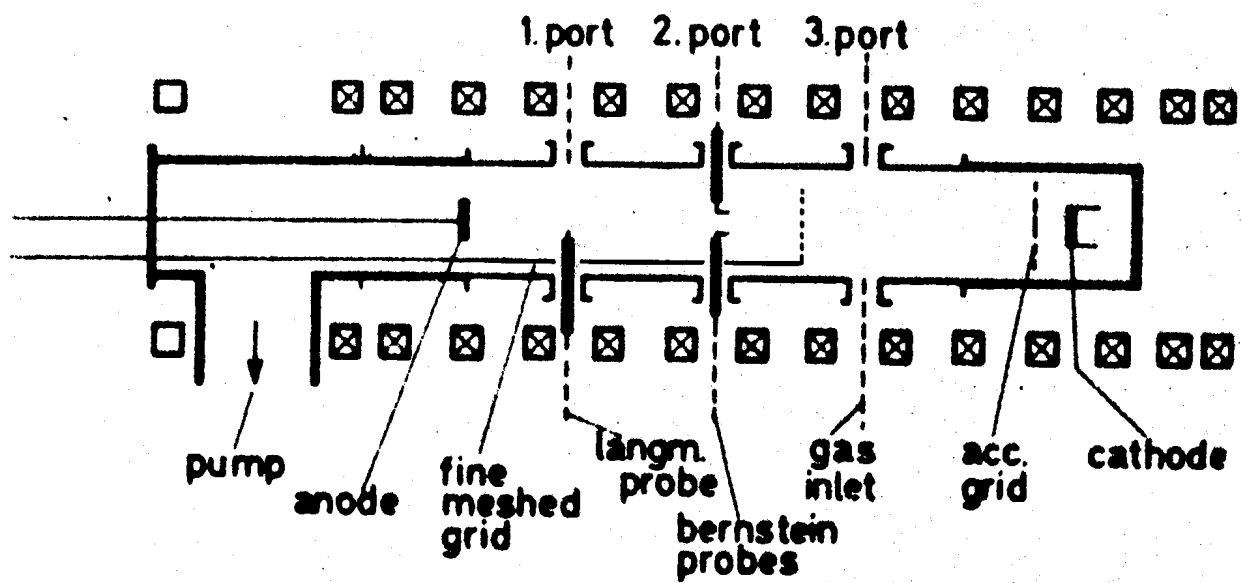


Fig. 1

DISCHARGE CHARACTERISTICS

ARGON $p = 5 \cdot 10^{-4}$

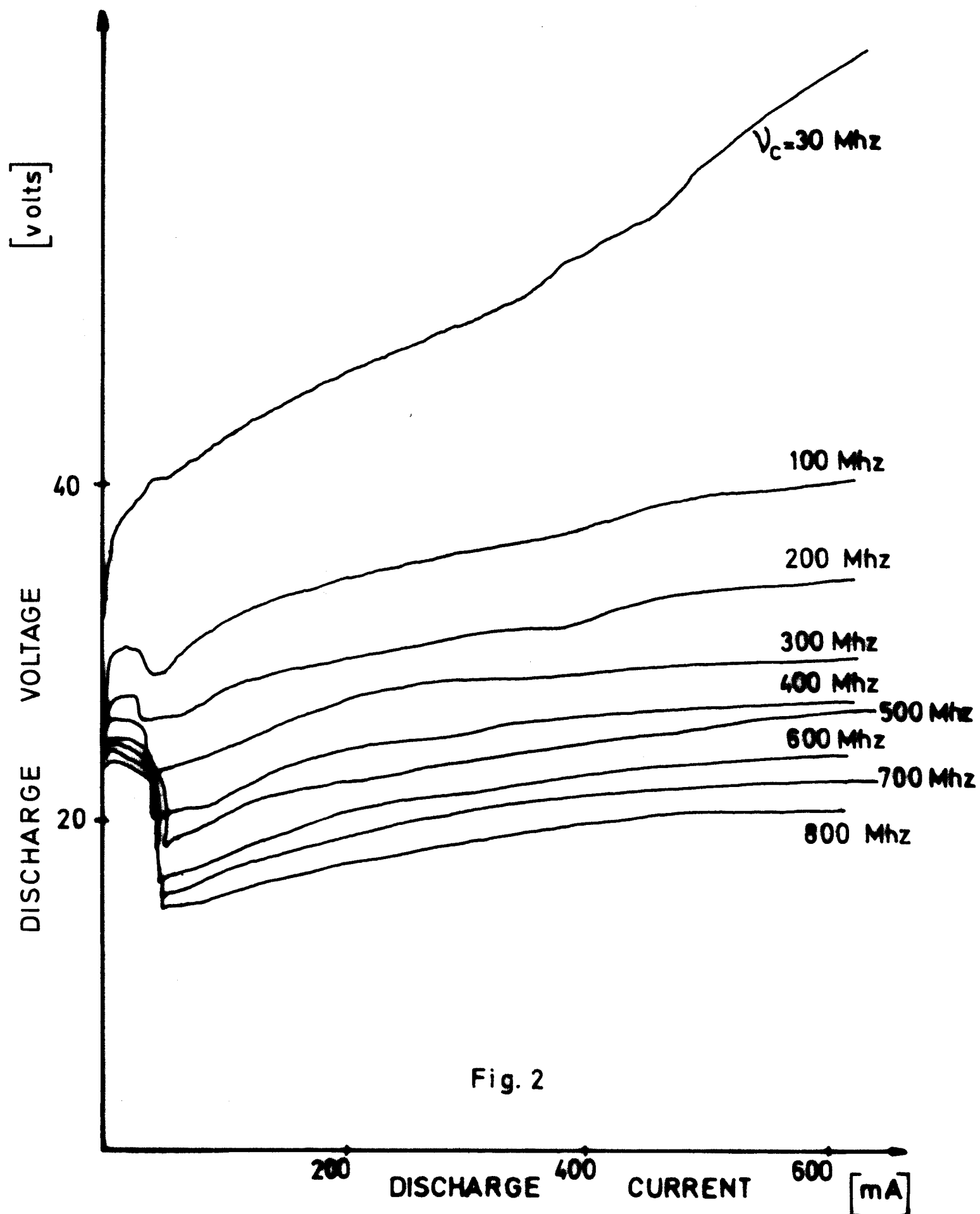


Fig. 2

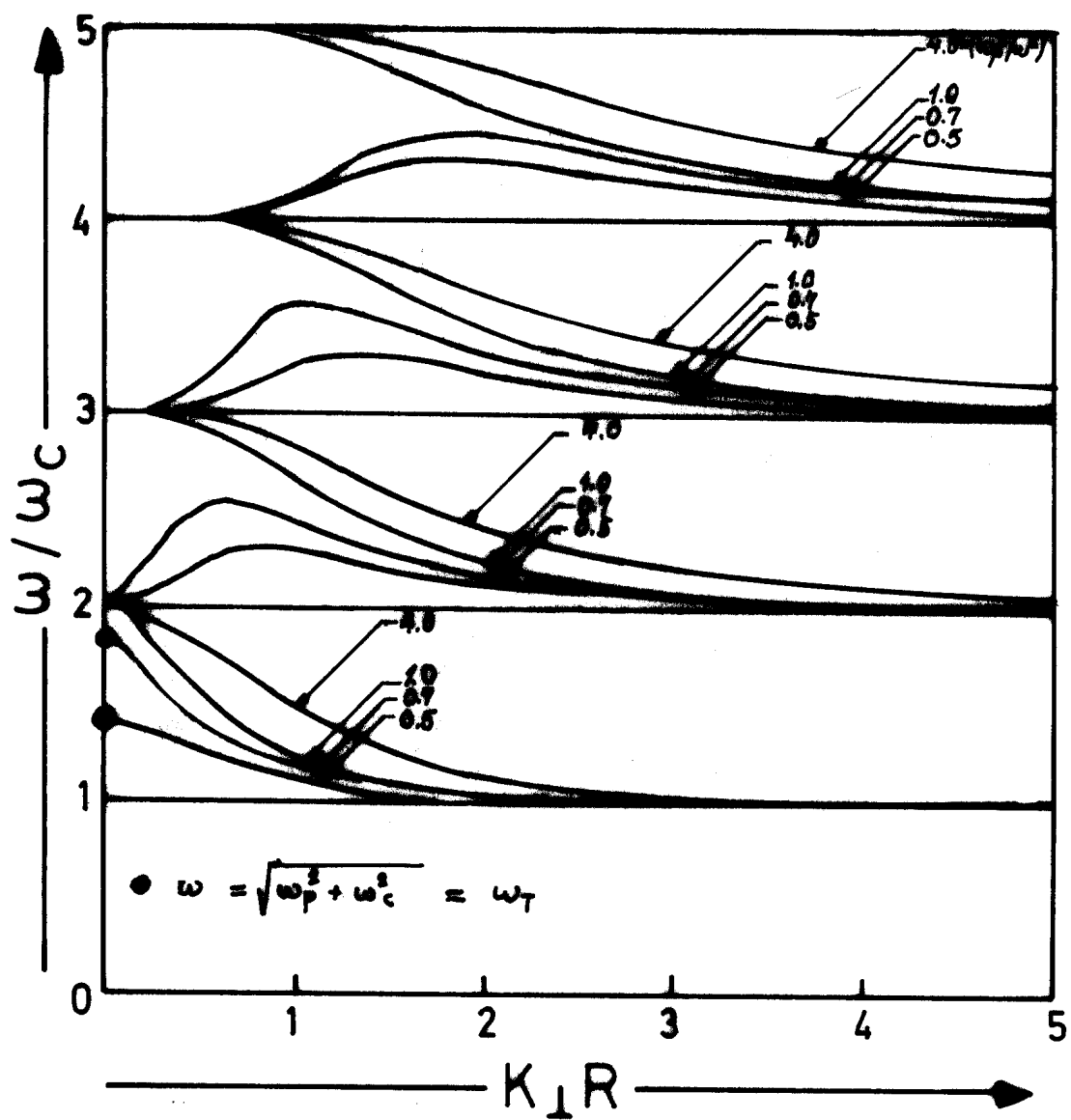


Fig. 3

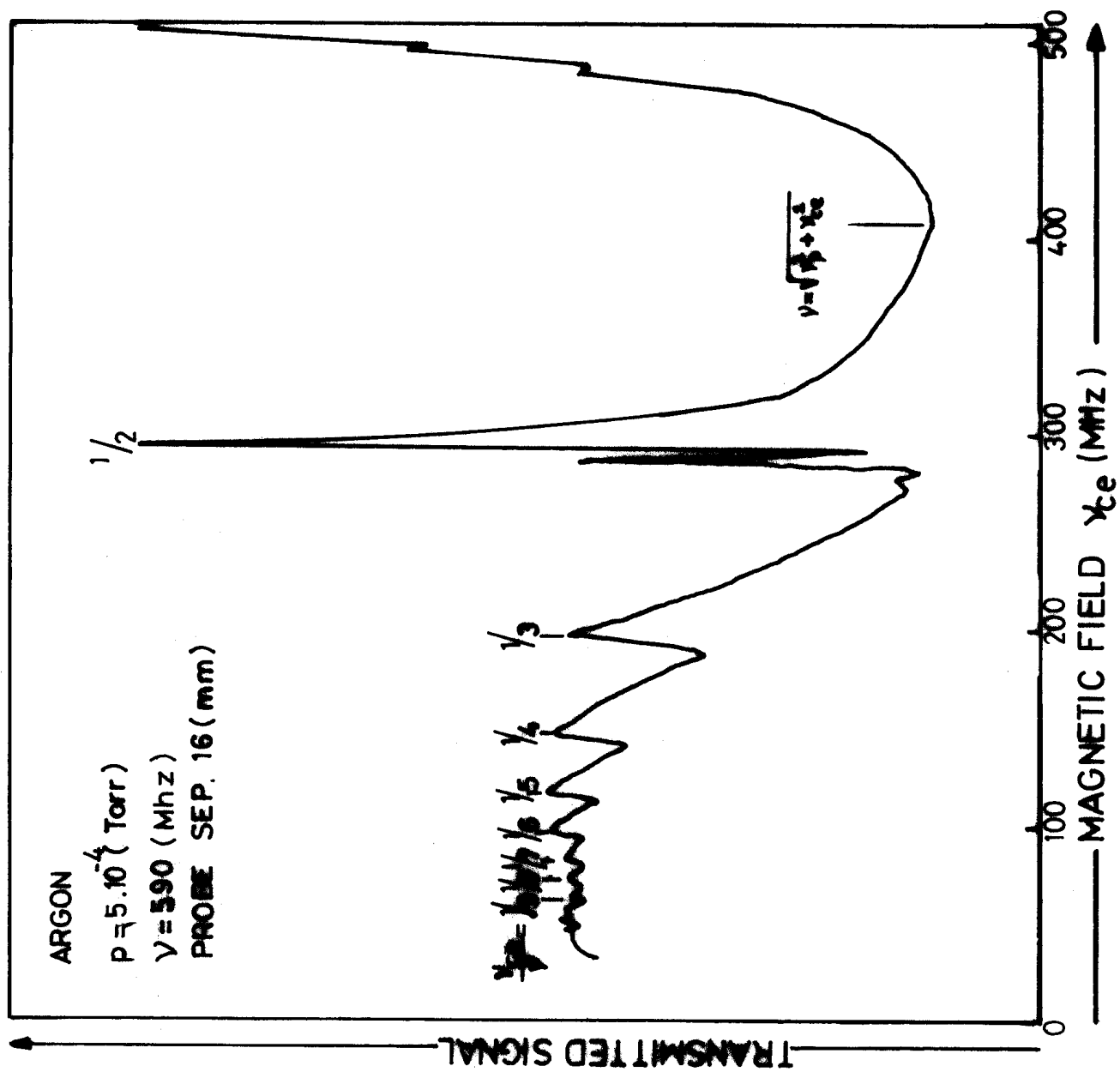


Fig.4

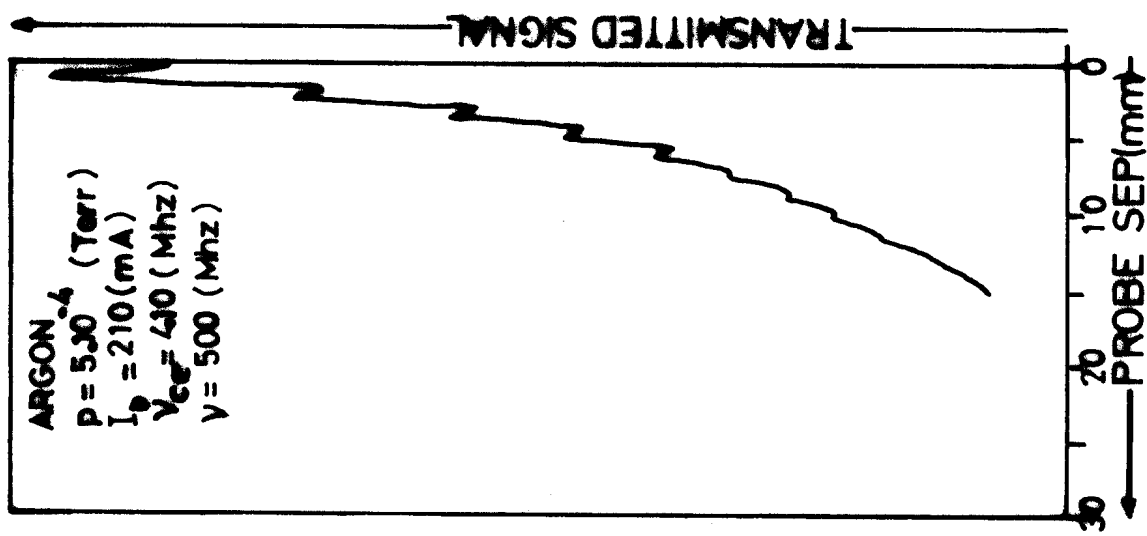


Fig.5

ANODE CHARACTERISTIC

Argon .4
 $p = 5.10$
 $I_D = 150 \text{ mA}$
 $V_{ce} = 250 \text{ Mhz}$

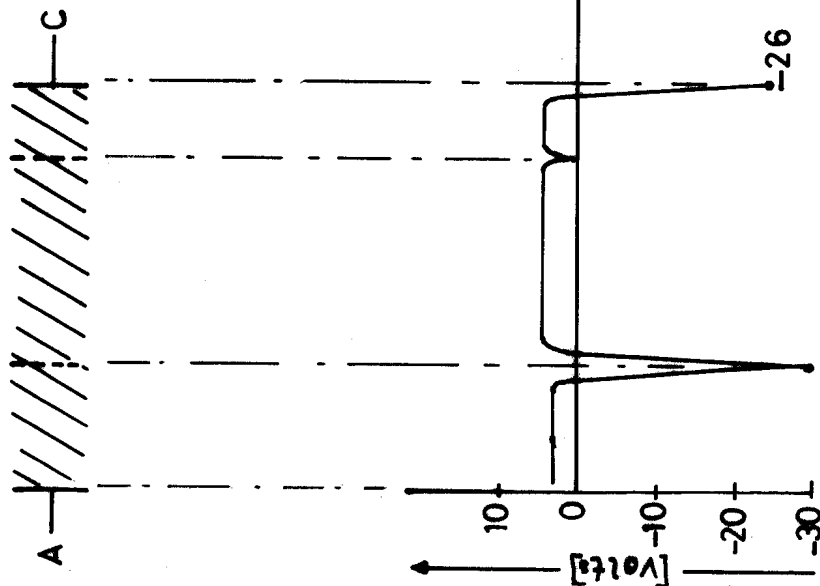
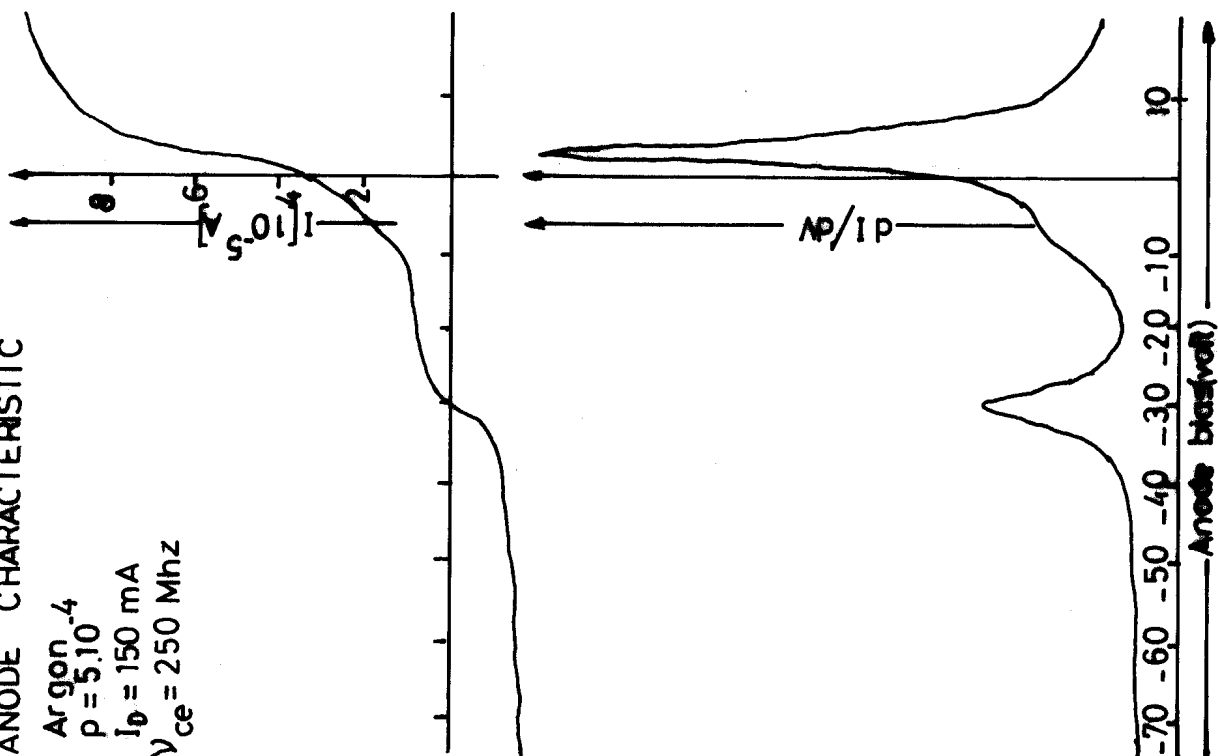


Fig.6

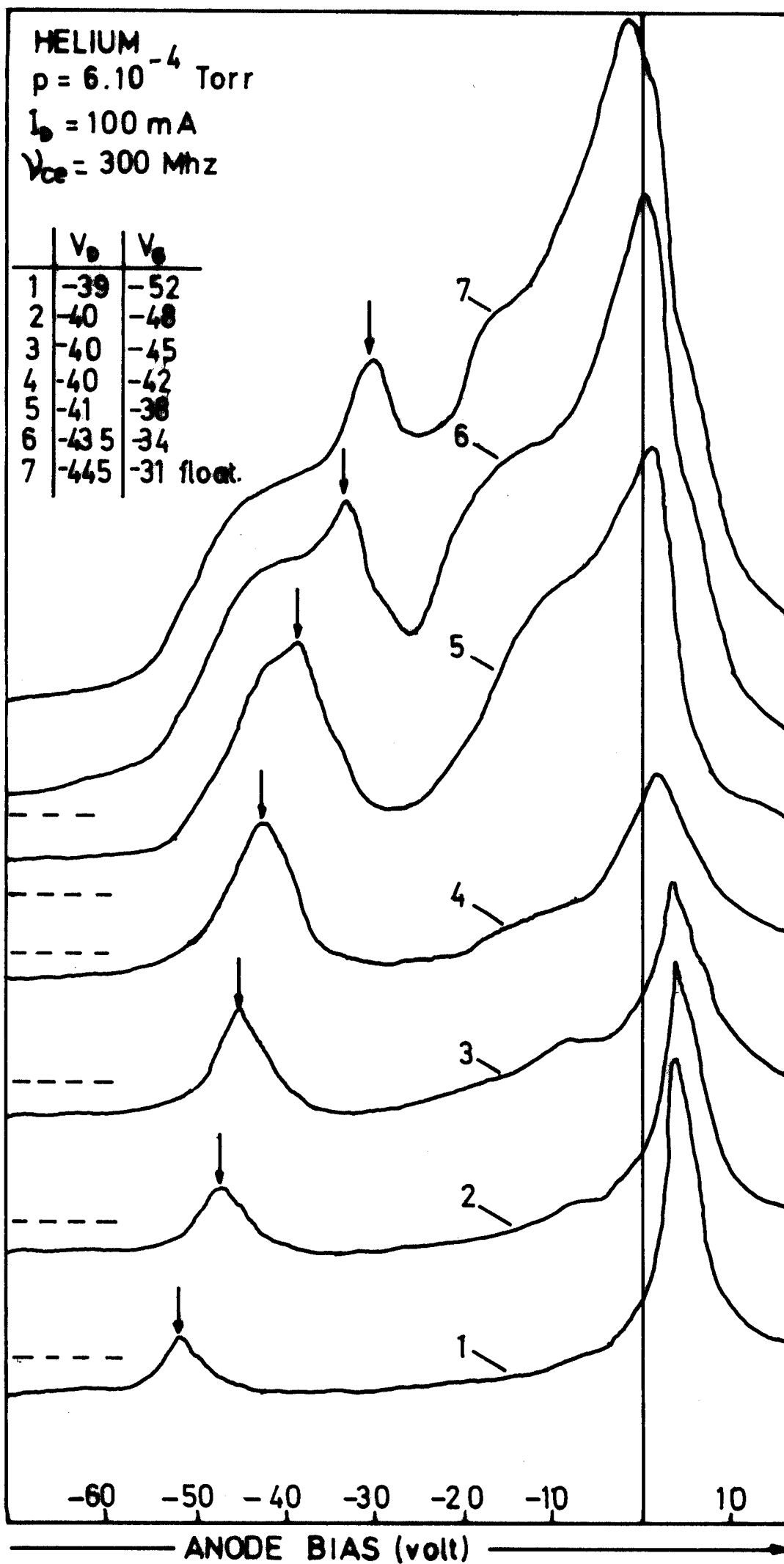


Fig. 7

$I_D = 135 \text{ mA}$

Argon $p = 5 \cdot 10^{-4}$

$\nu_{ce} = 300 \text{ MHz}$

	V_D	V_G
1	-26	-34
2	-26	-32
3	-26.5	-29 float.
4	-26.5	-26
5	-26.5	-24
6	-27	-22

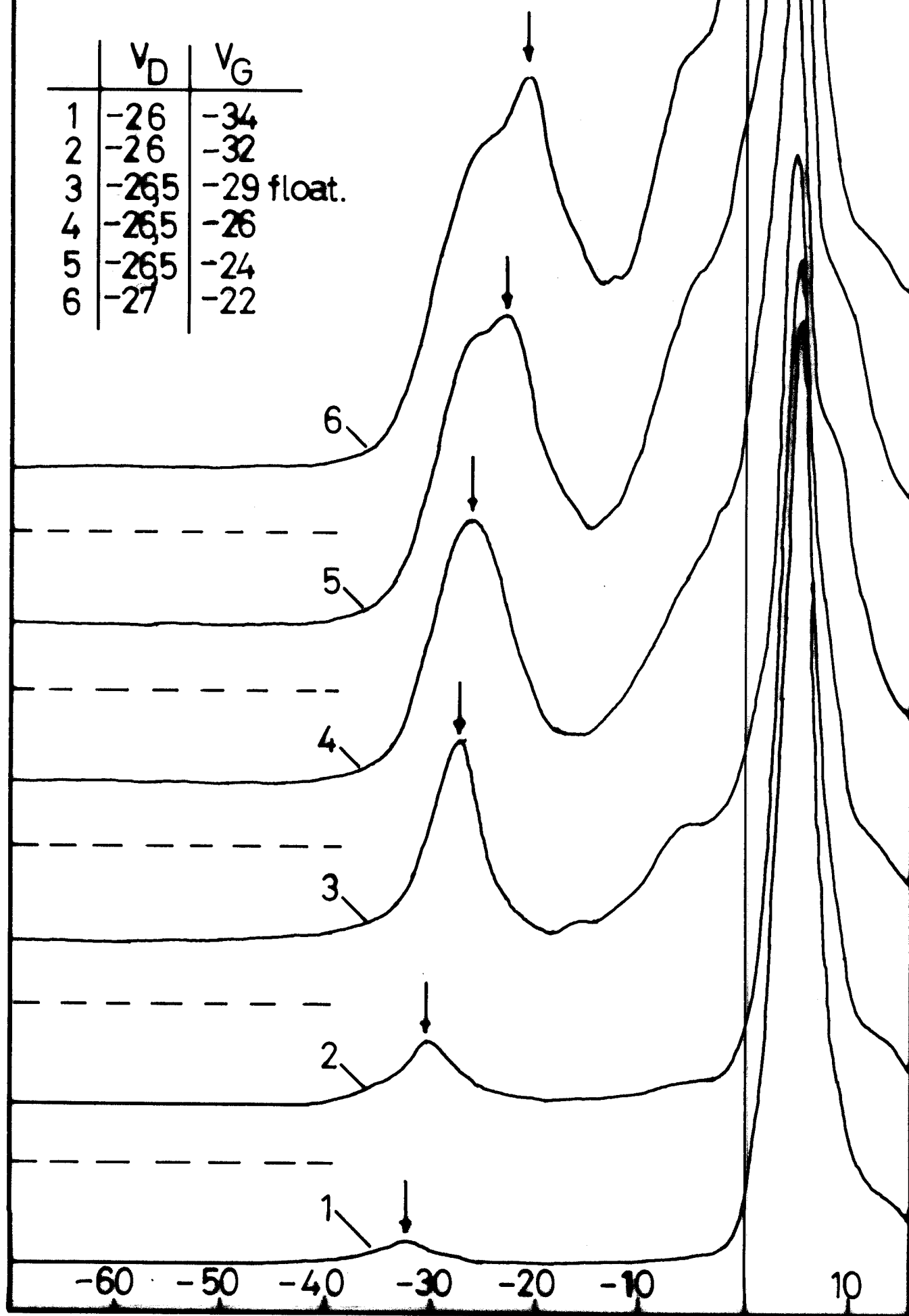


Fig. 8

$I_D = 200\text{mA}$
 $\nu_c = 250\text{MHz}$

Nitrogen
 $p = 9 \cdot 10^{-4}$

	V_D	V_G
1	-29	-40
2	-29	-35
3	-29	-33
4	-29	-31
5	-30	-29
6	-30	-27
7	-30	-25 float.
8	-30	-23
9	-30	-20

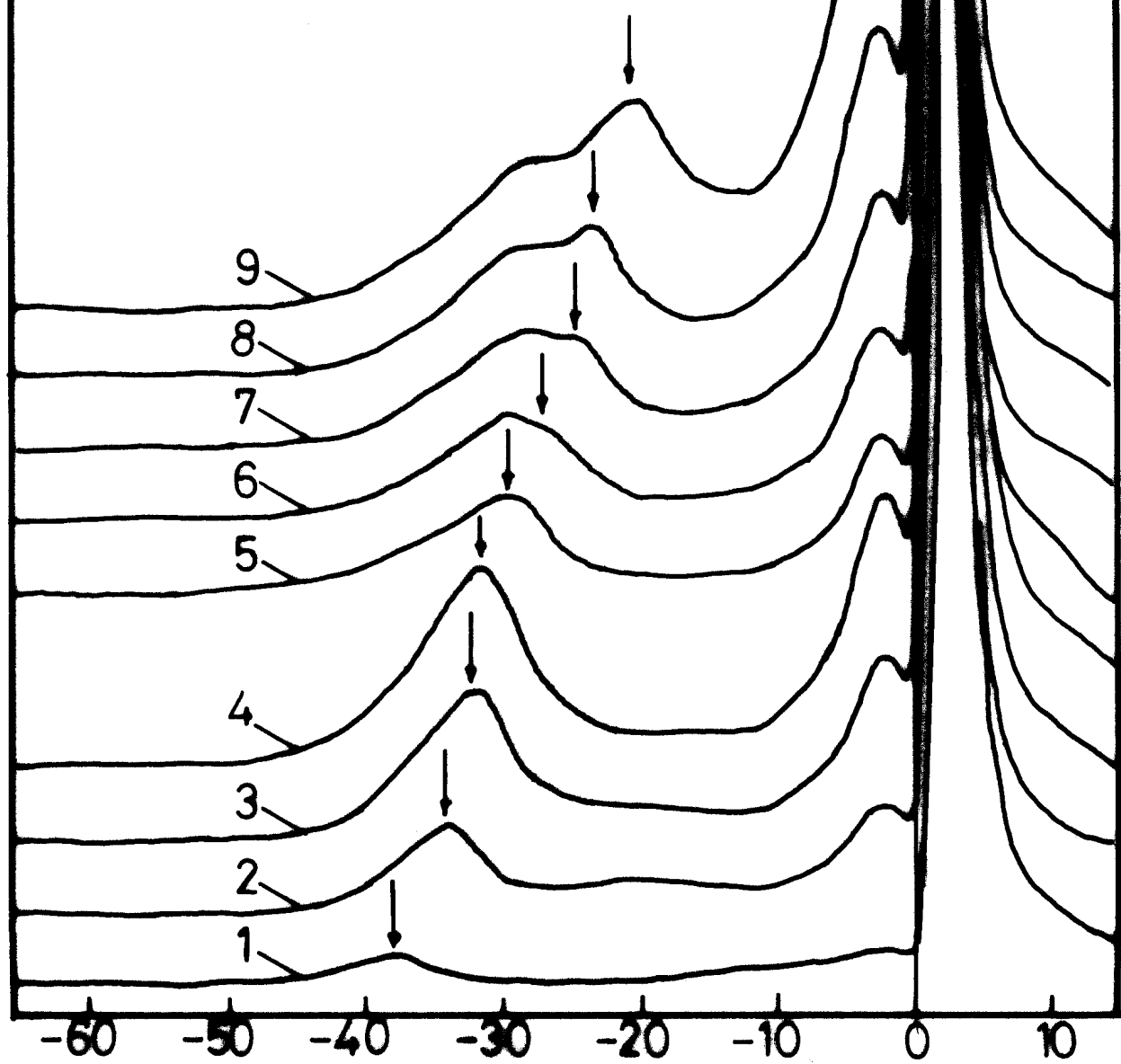


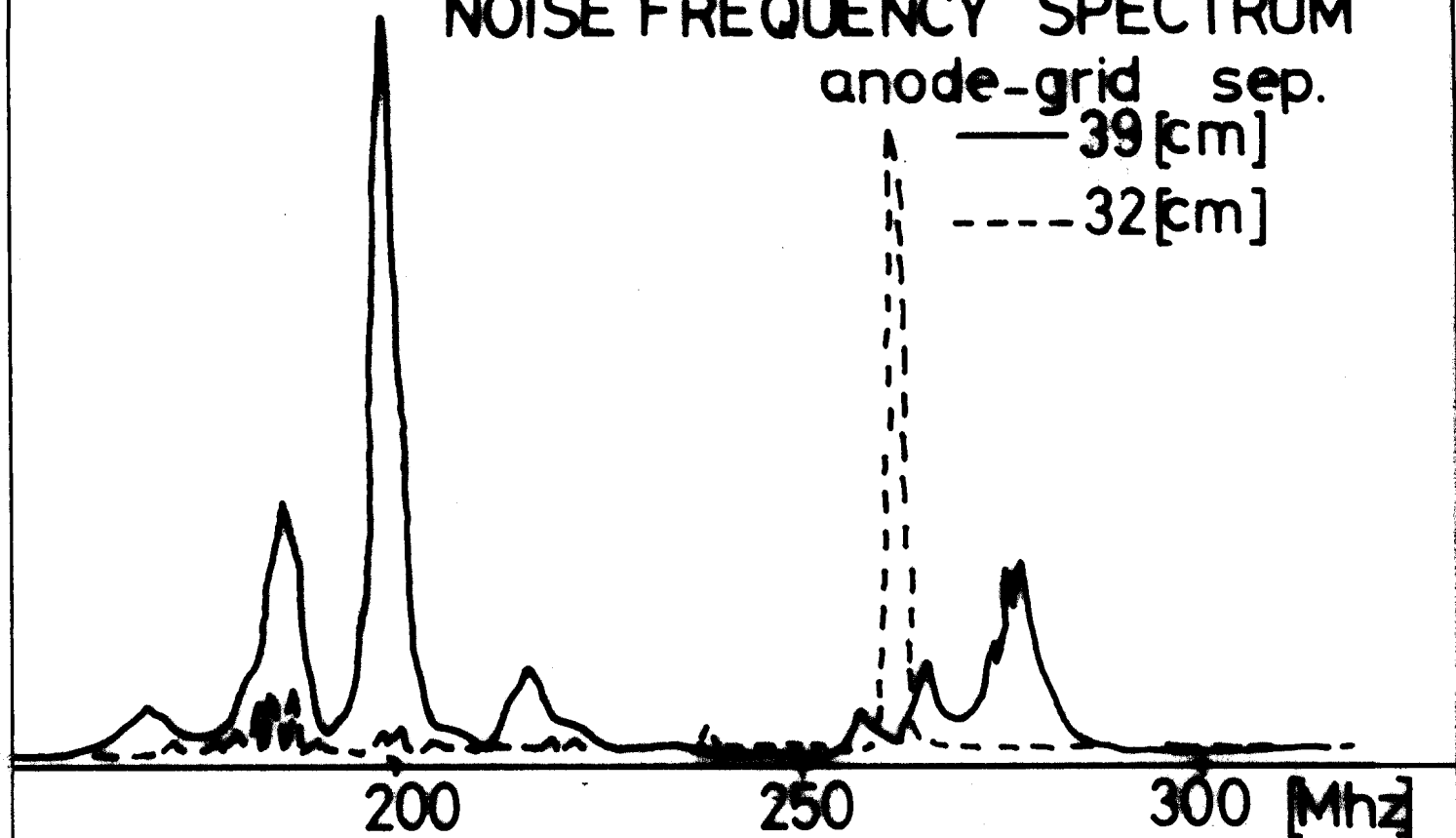
Fig.9

NOISE FREQUENCY SPECTRUM

anode-grid sep.

— 39 [cm]

--- 32 [cm]



$\nu_p = 350$ [MHz]

$\nu_c = 330$ [—]

NOISE INTENSITY AT 201 MHz

anode grid sep. 39 cm

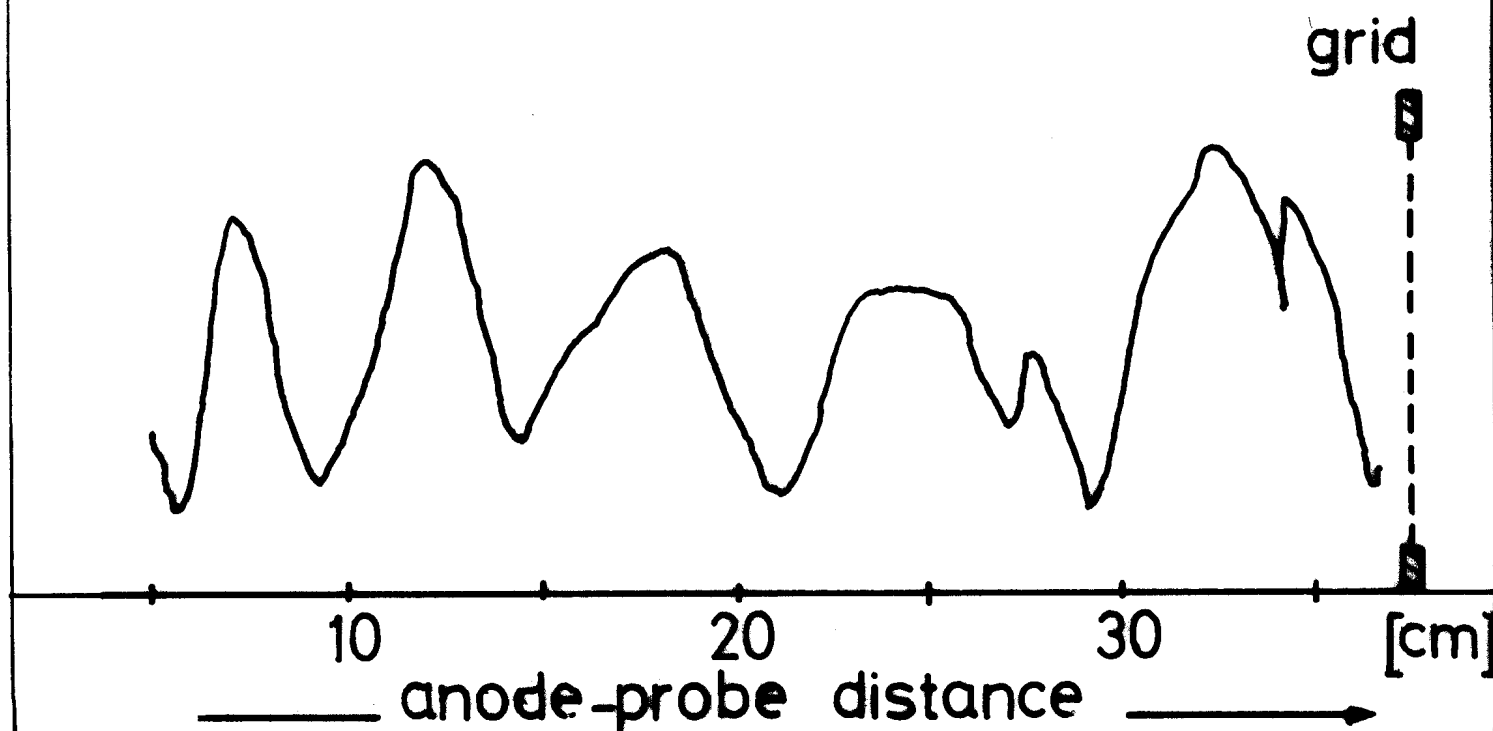


Fig.10